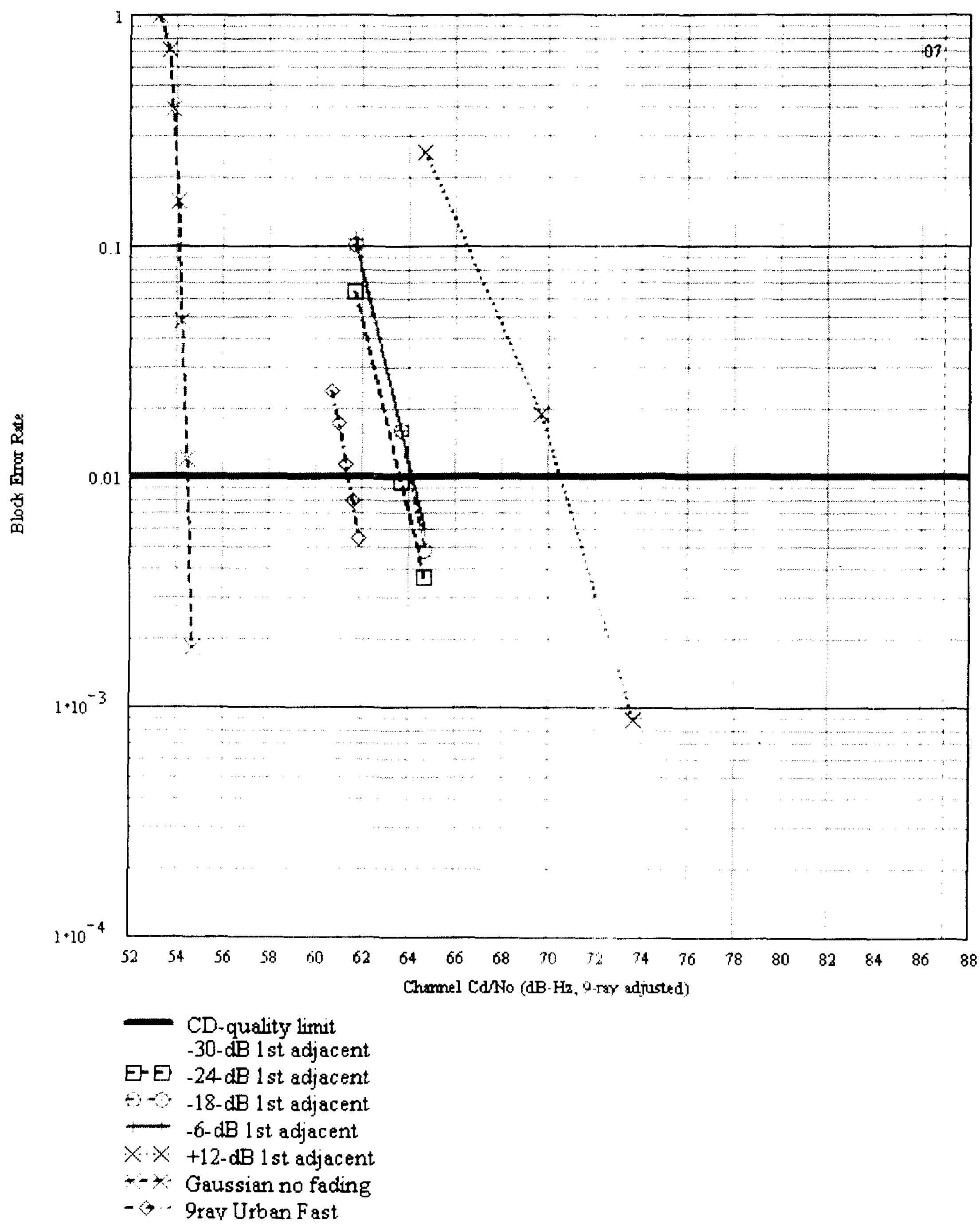
Figure E-8: Block Error Rate Results of the All-Digital System in 9-Ray Urban Fast Fading with One Independently Faded First Adjacent Interferer



3.2.2 Rayleigh Fading

Simulations were performed in the following selective fading environments, in the absence of interference. Extrapolations to the all-digital system are provided below. The block error rate results are shown in Figure E-9, and summarized in Table E-6.

3.2.2.1 Urban Slow[20] - The margin between the TOA and the analog 54-dBu protected contour is about 19 dB in an urban slow-fading channel and a 10,000 K Gaussian noise environment.[21]

3.2.2.2 Urban Fast[22] - The margin between the TOA and the analog 54-dBu protected contour is about 25.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment.

3.2.2.3 Rural Fast[23] - The margin between the TOA and the analog 54-dBu protected contour is about 30.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment.

3.2.2.4 Terrain Obstructed Fast[24] - The margin between the TOA and the analog 54-dBu protected contour is about 28.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment.

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[20] Refer to Table E-1 for a definition of this profile.

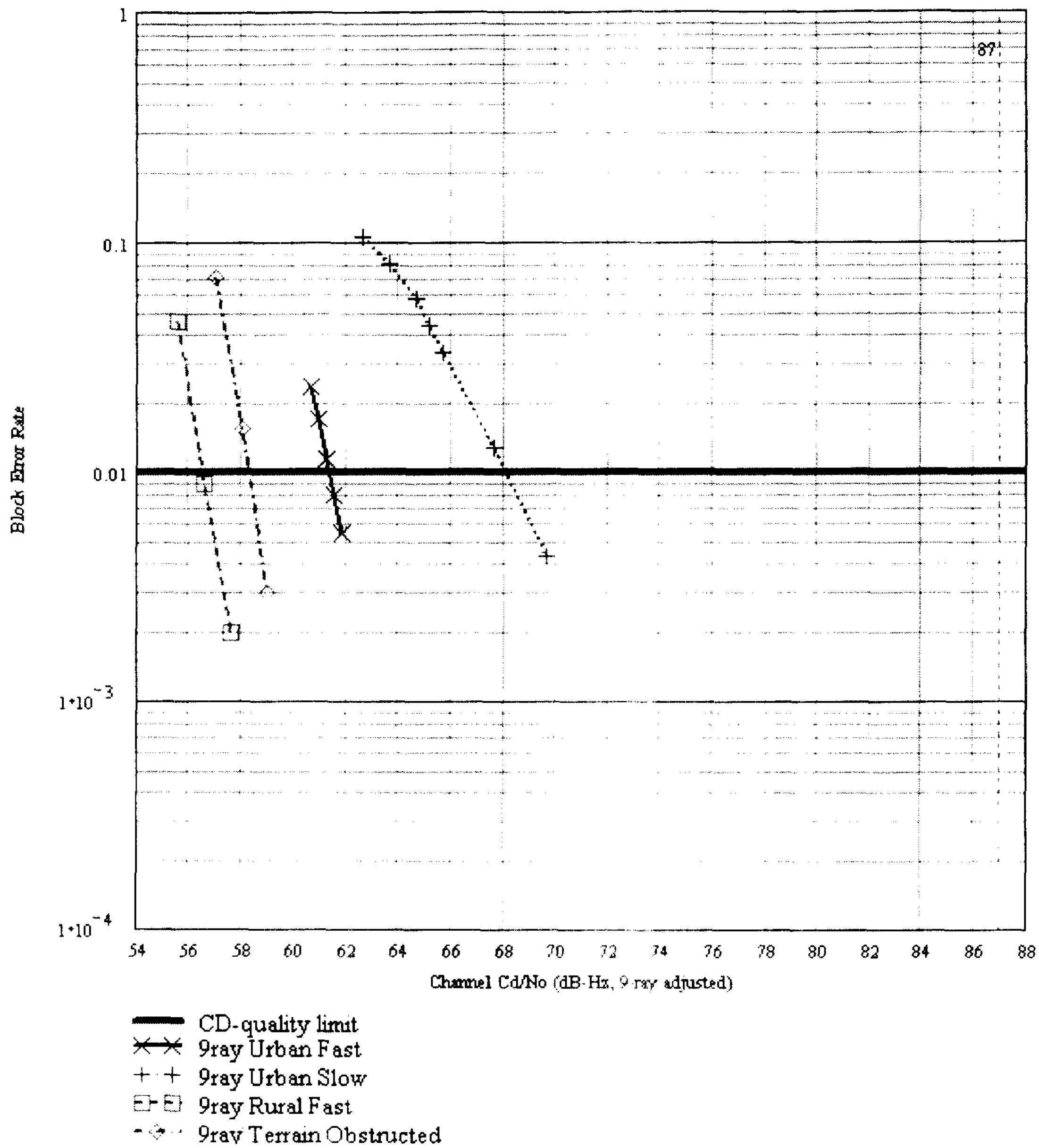
[21] Note that performance in this and other slowly fading environments can be improved by increasing the size of the interleaver.

[22] Refer to Table E-2 for a definition of this profile

[23] Refer to Table E-3 for a definition of this profile

[24] Refer to Table E-4 for a definition of this profile

Figure E-9 Block Error Rate Results of the All-Digital System in Different Types of 9-Ray Fading



3.2.3 In the Presence of Independently Faded Interference

This interference is comprised of various combinations of upper and lower first adjacent and second adjacent signals, as well as co-channel signals. The interferers may be analog, hybrid, or all-digital. Each interferer in a given scenario is passed through the same type of Rayleigh fading channel as the desired signal; however, all signals are independently faded, and are therefore uncorrelated.

3.2.3.1 Co-Channel Interference

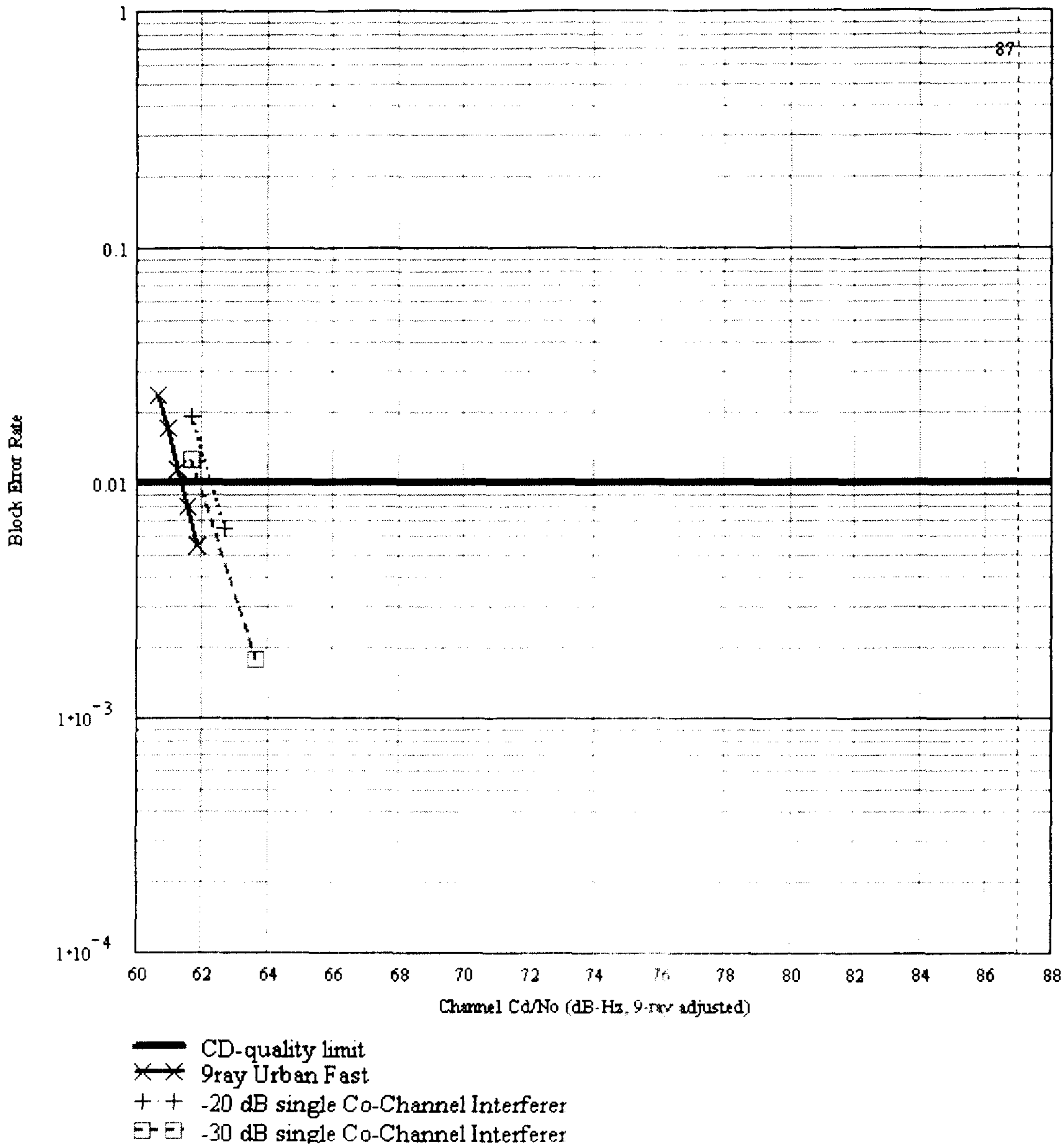
Properly spaced Class B stations are protected to the 54-dBu contour from co-channel interference exceeding 34 dBu in 50 percent of the locations for 10 percent of the time. Based on this information, a number of observations can be made regarding the character of co-channel interference to an all-digital signal of interest.

An analog interferer will usually be at least 20 dB lower in power than the analog portion of a desired hybrid signal at the 54-dBu analog protected contour. Recall that the total power in the all-digital signal is about 11.5 dB higher than the power in the hybrid DAB sidebands (which are 22 dB below the power in the host FM). Therefore, the total power in the all-digital signal is 10.5 dB below the total power in the analog portion of the hybrid signal. As a result, the total power of an analog interferer will usually be at least 20 - 10.5 = 9.5 dB below the total power in the all-digital signal at the 54-dBu protected contour In addition, there is little frequency overlap between the interferer and the desired digital sidebands. Thus, a co-channel interferer that is purely analog will have a minor effect on the performance of the all-digital signal.

A hybrid co-channel interferer should likewise have a minor effect on the performance of the all-digital signal. At the 54-dBu analog protected contour, the interfering digital sidebands will usually be at least 30 dB lower in power than the all-digital signal (+30-dB D/U), while the analog portion of the hybrid interferer will usually be at least 9.5 dB lower in power, with minimal frequency overlap. Performance has been quantified via simulation. A –20-dB hybrid co-channel interferer was applied to the desired all-digital signal in an urban fast-fading environment (+30-dB D/U). The block error rate results are shown in Figure E-10, and are summarized in Table E-6. Figure E-10 indicates that adding a –20-dB hybrid co-channel interferer degrades performance by less than 1 dB: margin between the TOA and the analog 54-dBu protected contour is about 25 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a –20-dB co-channel hybrid interferer (+30-dB D/U).

An all-digital co-channel interferer will have a minimal effect on the performance of the all-digital desired signal, since it will usually be at least 20 dB lower in power at the 54-dBu analog protected contour. This effect has been extrapolated from the hybrid simulations. The block error rate results are shown in Figure E-10, and are summarized in Table E-6. Figure E-10 indicates that adding a –20-dB all-digital co-channel interferer degrades performance by about 1 dB: margin between the TOA and the analog 54-dBu protected contour is about 24.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a –20-dB co-channel all-digital interferer.

Figure E-10: Block Error Rate Results of the All-Digital System in Urban Fast 9-Ray Fading with a Single Co-Channel Interferer.



3.2.3.2 Single First Adjacent

Extrapolations from the hybrid IBOC simulations have been used to characterize the performance of an all-digital IBOC signal in the presence of a single first adjacent analog FM signal in a Rayleigh urban fast-fading channel. Properly spaced Class B stations are protected to the 54-dBu contour from first adjacent channel interference exceeding 48 dBu in 50 percent of the locations for 10 percent of the time. As a result, extrapolations were performed using first adjacent analog interferers of varying power, up to a level that is 6 dB below the power of the analog host in a hybrid system (or 4.5 dB above the total power in the all-digital signal).

The block error rate results are shown in Figure E-8, and summarized in Table E-6. Note that the performance does not significantly degrade as the interference level increases from -24 dB to -6 dB (relative to a hybrid analog portion). This phenomenon can be attributed to the First Adjacent Cancellation ("FAC") algorithm used in the receiver. Margin between the TOA and the analog 54-dBu protected contour is about 23 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a -6-dB first adjacent interferer.

Figure E-8 and Table E-6 also show performance in the presence of a single +12-dB first adjacent analog interferer. Although degraded relative to a -6-dB first adjacent, margin between the TOA and the analog 54-dBu protected contour is still about 16.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a +12-dB first adjacent interferer. This result is conservative, since the simulation's limited degree of FAC interference rejection did not completely cancel the adjacent channel. Practical receiver implementations could provide sufficient FAC interference rejection to effectively cancel significantly larger first adjacent interferers.

Performance in the presence of a first adjacent hybrid interferer will be similar to performance with a first adjacent analog interferer since the digital portion of the hybrid interferer does not overlap in frequency with the desired all-digital signal.

Performance in the presence of a first adjacent all-digital interferer will be similar to performance in the absence of interference, since the all-digital interferer does not overlap in frequency with the desired all-digital signal.

3.2.3.3 Second Adjacent(s) Interference

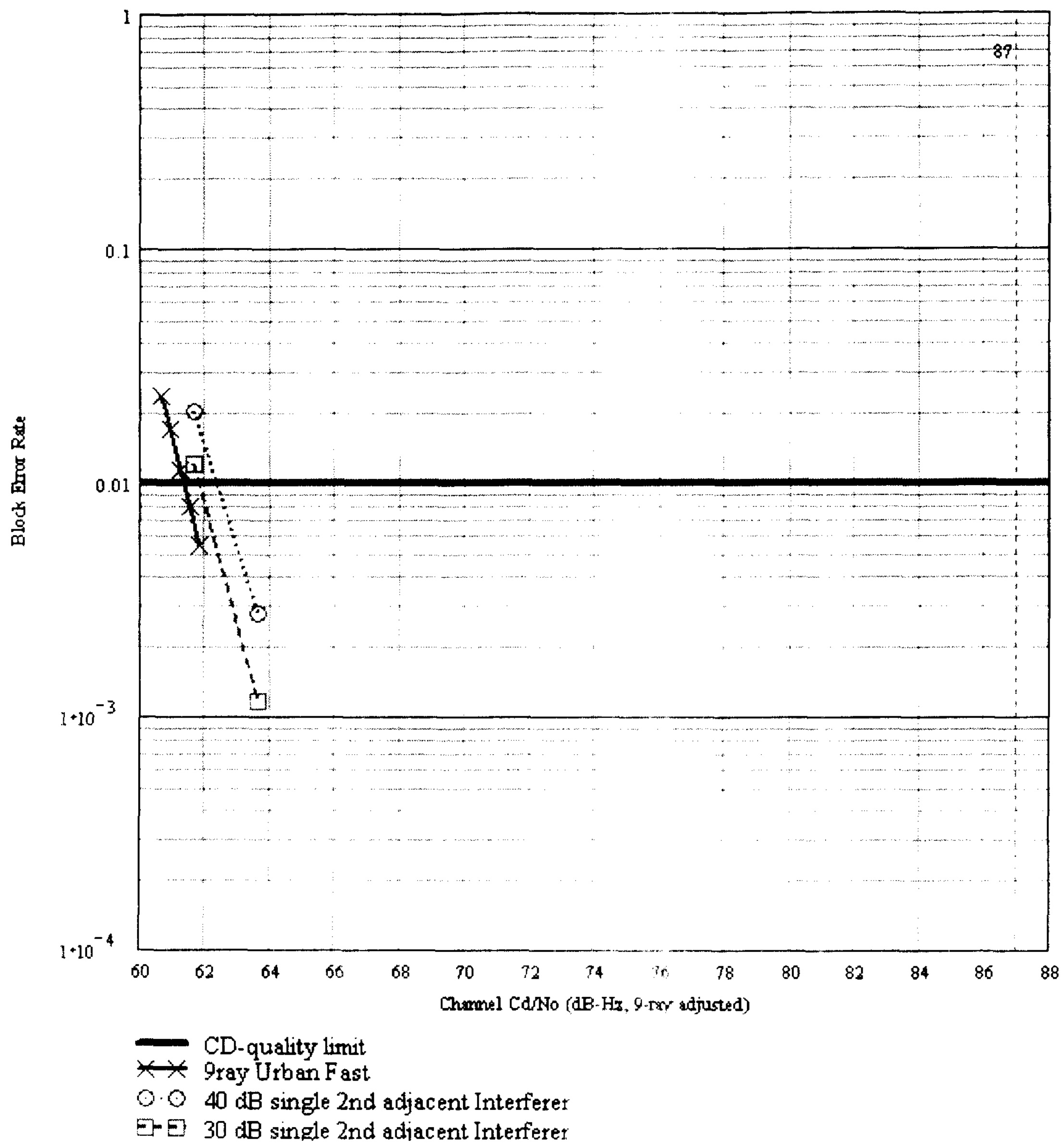
Properly spaced Class B stations are protected to the 54-dBu contour from second adjacent channel interference exceeding 94 dBu in 50 percent of the locations for 10 percent of the time. Based on this information, a number of observations can be made regarding the character of second adjacent interference to an all-digital signal of interest.

An analog second adjacent interferer will have a negligible effect on the performance of the all-digital signal, since it does not overlap in frequency with the desired all-digital signal.

A hybrid second adjacent interferer should have a minor effect on all-digital performance. Since the interference power could be 30 dB higher than the desired signal, digital interference sidelobes could spill into the desired all-digital signal. This effect has been quantified in simulation. A +40-dB hybrid second adjacent interferer was applied to the desired all-digital signal in an urban fast-fading environment (-30-dB D/U). The block error rate results are shown in Figure E-11, and are summarized in Table E-6. Figure E-11 indicates that adding a +40-dB hybrid second adjacent interferer degrades performance by less than 1 dB; margin between the TOA and the analog 54-dBu protected contour is about 25 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a +40-dB second adjacent hybrid interferer (-30-dB D/U).

An all-digital second adjacent interferer will have a greater effect on performance than a hybrid second adjacent, since its digital sidelobes are 10 dB higher. This effect has been extrapolated from the hybrid system simulations. A +40-dB all-digital second adjacent interferer was applied to the desired all-digital signal in an urban fast-fading environment. The block error rate results are shown in Figure E-11, and are summarized in Table E-6. Figure E-11 indicates that adding a +40-dB all-digital second adjacent interferer degrades performance by about 1 dB; margin between the TOA and the analog 54-dBu protected contour is about 24.5 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a +40-dB second adjacent all-digital interferer.

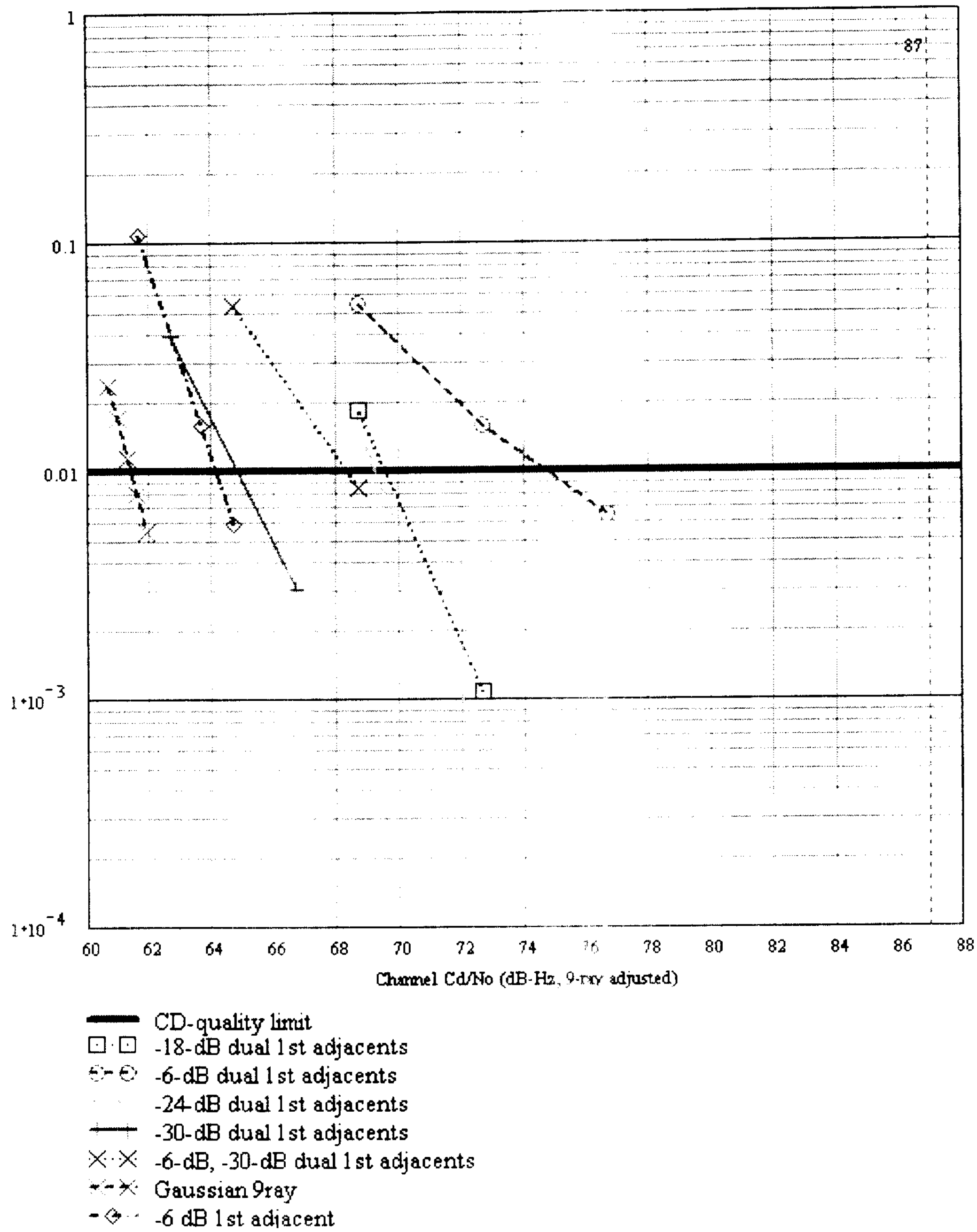
Figure E-11 Block Error Rate Results of the All-Digital System in Urban Fast 9-Ray Fading with a Single 2nd Adjacent Interferer



3.2.3.4 <u>Simultaneous Dual First Adjacent Interference</u>

Extrapolations from the hybrid IBOC simulations have been used to characterize the performance of an IBOC all-digital signal in the presence of two first adjacent analog FM signals in a Rayleigh urban fast-fading channel. Properly spaced Class B stations are protected to the 54-dBu contour from first adjacent channel interference exceeding 48 dBu in 50 percent of the locations for 10 percent of the time. As a result, extrapolations were performed using two first adjacent analog interferers of varying power, up to a level that is 6 dB below the power of the analog host in a hybrid system (or 4.5 dB above the total power in the all-digital signal). The block error rate results are shown in Figure E-12, and summarized in Table E-6.

Figure E-12 Block Error Rate Results of the All-Digital System in 9-Ray Urban Fast Fading with Two Independently Faded First Adjacent Interferers



With two analog first adjacent interferers whose power is 6 dB below the hybrid analog host, margin between the TOA and the analog 54-dBu protected contour is about 13 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment.

This scenario, with two very large first adjacent interferers, is much worse than the typical situation. As the interference levels are reduced, system performance improves accordingly, as shown in Figure E-12. All interference scenarios yield significant margin between the TOA and the analog 54-dBu protected contour; however, without the advantage of the receiver FAC algorithm, many of these scenarios would degrade system performance beyond the point of failure.

Performance in the presence of dual first adjacent hybrid interferers, or a combination of one hybrid and one analog first adjacent interferer will be similar to performance with two first adjacent analog interferers, since the digital portion of the hybrid interferer does not overlap in frequency with the desired all-digital signal.

Performance in the presence of dual first adjacent all-digital interferers will be similar to performance in the absence of interference, since the all-digital interferers do not overlap in frequency with the desired all-digital signal.

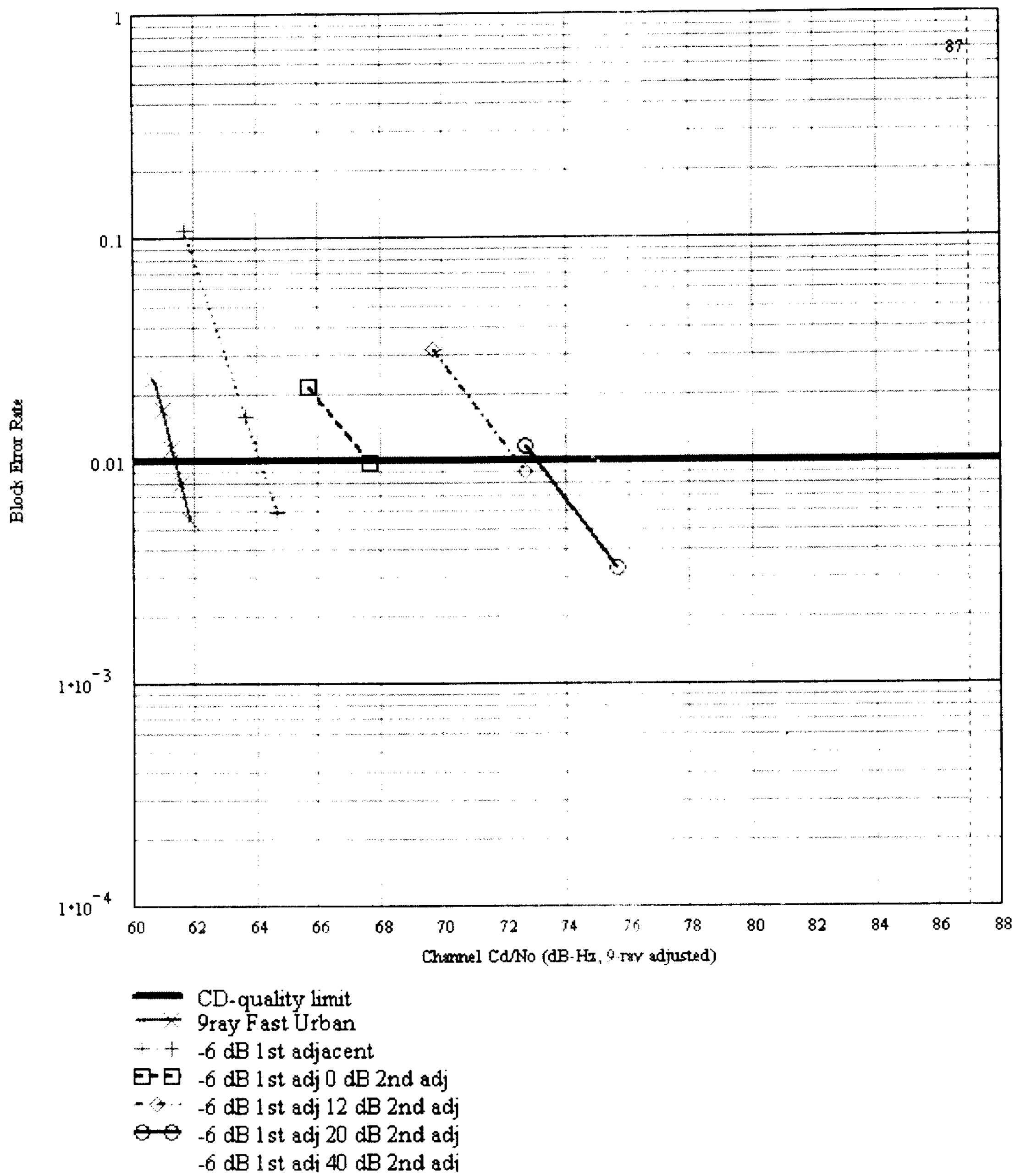
Performance in the presence of a combination of one all-digital and one hybrid first adjacent interferer will be similar to performance with a single first adjacent analog interferer, since neither the digital portion of the hybrid nor the all-digital interferer overlaps in frequency with the desired all-digital signal.

3.2.3.5 Simultaneous First and Second Adjacent Interference

Of particular interest is interference which consists of an analog first adjacent and a high-level digital second adjacent on the same sideband of the desired all-digital signal. Interaction of two such interferers in the receiver FAC algorithm can add noise to the desired all-digital signal. As a result, extrapolations from the hybrid IBOC simulations have been used to quantify the degradation in this interference scenario.

Figure E-13 and Table E-6 show the impact as an upper second adjacent hybrid or all-digital interferer is increased in power in the presence of a -6-dB upper first adjacent analog or hybrid interferer. Note that all simulated interference scenarios yield significant margin between the TOA and the analog 54-dBu protected contour

Figure E-13: Block Error Rate Results of the All-Digital System in 9-Ray Fast Urban Fading with an Independently Faded Lower First Adjacent Interferer and Lower Second Adjacent Interferer



The worst-case scenario, illustrated in Figure E-14, is comprised of an upper first adjacent analog or hybrid interferer whose analog power is 6 dB below the desired FM power (if the desired signal were hybrid), and an upper second adjacent hybrid or all-digital interferer whose digital power is 40 dB above the desired all-digital power. (This is highly unlikely, since these first and second adjacents are themselves first adjacents.) Margin between the TOA and the analog 54-dBu protected contour is about 12 dB in an urban fast-fading channel and a 10,000 K Gaussian noise environment in the presence of a -6-dB first adjacent analog or hybrid interferer and a +40-dB second adjacent hybrid or all-digital interferer. As the second adjacent interference levels are reduced, system performance improves accordingly, as shown in Figure E-13.

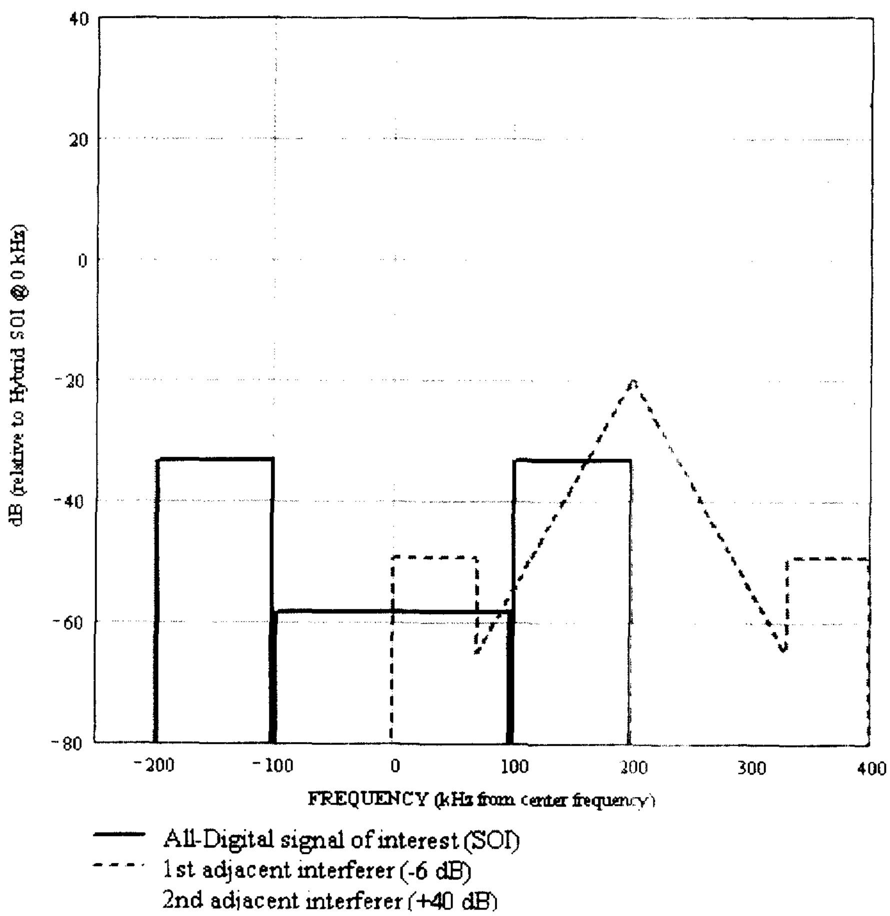


Figure E-14 - Simultaneous First and Second Adjacent Interference to All-Digital Signal of Interest

4.0 Existing FM Analog Performance

USADR has minimized the impact of IBOC DAB on existing analog signals, while optimizing digital performance and audio quality. A variety of simulations and analyses have characterized the performance of an analog FM signal in the presence of hybrid IBOC sidebands and various types of interference. This section describes the impact on audio performance, SCAs, and stereo subcarrier demodulation when IBOC DAB sidebands are added to the host FM signal. In addition, the effects of first adjacent channel, second adjacent channel, and co-channel interference from analog, hybrid, and all-digital IBOC signals will also be discussed.

All simulations were run in a static environment. This was done to clearly illustrate the impact that DAB sidebands and interference would have on the analog signal, without including the effects of fading, which complicates the analysis. In addition, FM receiver performance metrics (such as SNR) are typically measured in a static environment, thus allowing easy comparison to published receiver specifications.

USADR modeled a typical automobile FM stereo receiver. Simulated results and conclusions presented herein are based on performance of this receiver.

4.1 Impact of digital signal on analog host FM performance

USADR has investigated the impact of adding IBOC DAB sidebands to an existing FM signal. Of particular interest is their effect on audio channel SNR, SCAs, and stereo subcarrier demodulation.

4.1.1 Main audio channel performance

Simulations have provided valuable insight into the character of analog FM post-detection noise in the presence of IBOC DAB sidebands. For instance, results indicate that the audio noise level increases with the deviation of the analog FM signal. In particular, a significant rise in the post-detection noise power spectral density ("PSD") was observed as the analog FM deviation varied from minimum to maximum in the presence of an IBOC DAB signal. The nonlinear analog FM detector is responsible for intermodulating overlapping portions of the host analog and DAB spectra. The products are folding back into the post-detection audio band and raising its noise floor.

Although these results are intriguing, they do not predict a degradation in host analog FM audio quality due to IBOC DAB. Because the DAB-induced post-detection noise floor increases in proportion to the deviation of the analog FM signal, the effect is self-masking: audio noise will be lowest during quiet passages, and highest only when the audio is loudest. Simulations have confirmed this phenomenon.

The absolute level of host analog FM degradation will depend on the particular configuration of DAB. To determine the relationship between DAB location and audio signal-to-noise ratio, a number of performance tests were run when DAB noise would be most audible – during quiet passages of minimum analog FM deviation. Simulations were performed in which the receiver audio dynamic range was measured with only a 10%-deviated, 19-kHz-pilot-modulated analog FM signal and a DAB signal input to an FM stereo receiver located at the transmitter. The total power of the DAB signal was 22 dB below the power of the analog FM carrier. In the first four tests, the DAB was modulated using orthogonal frequency-division multiplexing ("OFDM") with 4750-symbol-per-second quadrature phase-shift keying ("QPSK") carriers using rectangular pulse shaping. The fifth test employed DAB with four times the number of OFDM carriers -- each occupying one-fourth the bandwidth (1187.5 Hz) -- and root-raised-cosine pulse shaping (to reduce spectral sidelobes that interfere with the host analog FM). In each test, the spectral occupancy of the DAB signal was changed: the start frequency was varied with respect to the FM center frequency, while the stop frequency was fixed at 197 kHz. Table E-7 summarizes the results.

Table E-7 - Audio Dynamic Range at Transmitter (peak-to-noise-floor SNR)	
DAB start frequency	**Audio SNR (dB/15 kHz)**
78 kHz	64.7
100 kHz	67.3
124 kHz	68.3
129 kHz	68.8
129 kHz, pulse shaped	77.6

These results indicate that moving the DAB away from the analog FM carrier, increasing the number of DAB carriers, and pulse shaping the transmitted DAB symbols to reduce spectral sidelobes will significantly reduce the interference to the host analog FM.

Modulation and coding characteristics of the DAB signal have been traded for spectral occupancy to meet these goals. Additional audio simulations indicated that an SNR of 77.6 dB in the modeled receiver during quiet passages renders DAB-induced audio noise imperceptible to the listener. Furthermore, implementation constraints limit the SNR of typical receivers to around 59 dB.[25] The noise created within these receivers could mask any degradation caused by IBOC DAB. However, actual impact is a function of receiver design, signal strength, listening environment, radio frequency environment, and audio content.

The -22-dB, 129-kHz pulse-shaped DAB configuration is used as the baseline for the balance of this discussion.

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[25] 59 dB is the average SNR of 5 receivers tested in "Digital Audio Radio Laboratory Tests Transmission Quality Failure Characterization and Analog Compatibility" Electronic Industries Association, Appendix H, dated August 11, 1995.

4.1.2 SCA performance

Subsidiary Communications Authorizations ("SCAs") are optional channels multiplexed onto the baseband stereo spectrum from 53 kHz to 100 kHz. The SCA signal, which can be analog or digital, is transmitted by some FM stations for the use of private subscribers who typically pay for program material. Simulations were used to determine the impact of SCAs on IBOC DAB host FM performance, and to determine the impact of DAB on the performance of SCAs. SCAs with 10% deviation at 67 kHz and 92 kHz were simulated because they represent a large percentage of operational subcarriers.

In current analog FM, SCAs generally cause negligible interference to the host FM signal. However, in the hybrid DAB system, the addition of SCAs could increase the host FM audio noise floor due to the DAB/FM intermodulation effect described above. Figure E-15 illustrates stereo subcarrier sensitivity to 92-kHz SCAs when subject to a pulse-shaped ("PS") DAB signal starting at 129 kHz. In this case, the 92-kHz SCA reduces the host FM audio SNR from 77.6 to 69.8 dB; however, this noise level is still be too low to produce audible effects in the modeled receiver. Figure E-16 shows that SCAs located at 67 kHz have even less impact on audio performance.

Due to their location at the high end of the baseband spectrum, some SCAs currently operate at low SNRs because the post-detection noise floor increases with the square of the frequency. When DAB is added, the deviation of a wideband host analog FM signal into its IBOC DAB signal produces intermodulation which increases the post-detection noise floor, particularly in the higher baseband frequencies (since this is nearest the location of the pre-detection DAB). Moreover, the noise masking effect described above does not apply to SCAs, since their audio may be quiet while the main audio channel, at peak deviation, is causing an increase in the SCA noise floor.

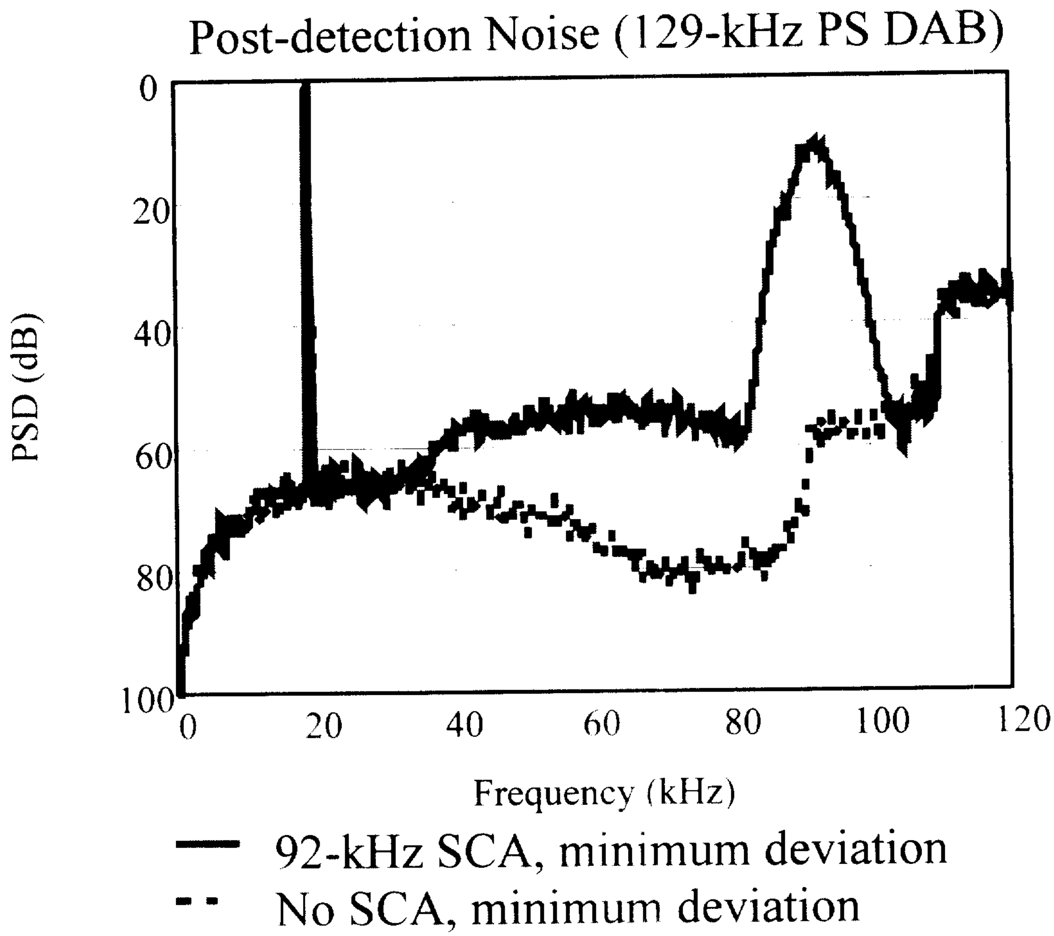

Figure E-15 - Effects of 92-kHz SCA

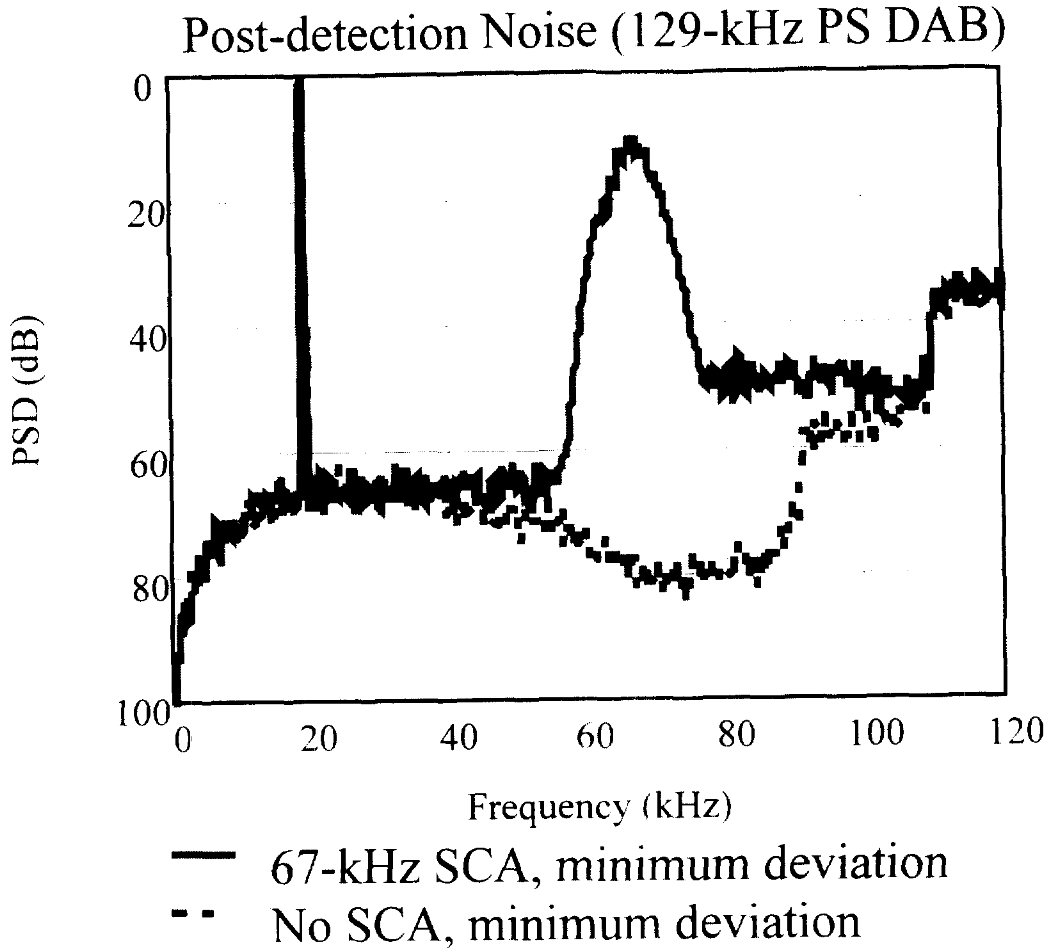

Figure E-16 - Effects of 67-kHz SCA

Simulations were performed using SCAs with peak-deviated audio signals in the presence of a -22-dB, 129-kHz pulse-shaped DAB signal. Figure E-17 indicates that the SNR of a 67-kHz SCA (in a 10-kHz bandwidth) is 25-30 dB at the transmitter when the main audio channel is near maximum deviation. For 92-kHz SCAs, the SNR is 20-25 dB, as illustrated in Figure E-18.

Simulations showed that without DAB, the FM signal alone (without additional noise) yielded a typical post-detection SCA SNR of 40 dB The increase in noise floor may not pose a problem for digital SCAs (e.g., Seiko and Radio Broadcast Data System), since they should be robust enough to operate at reasonably low SNRs.

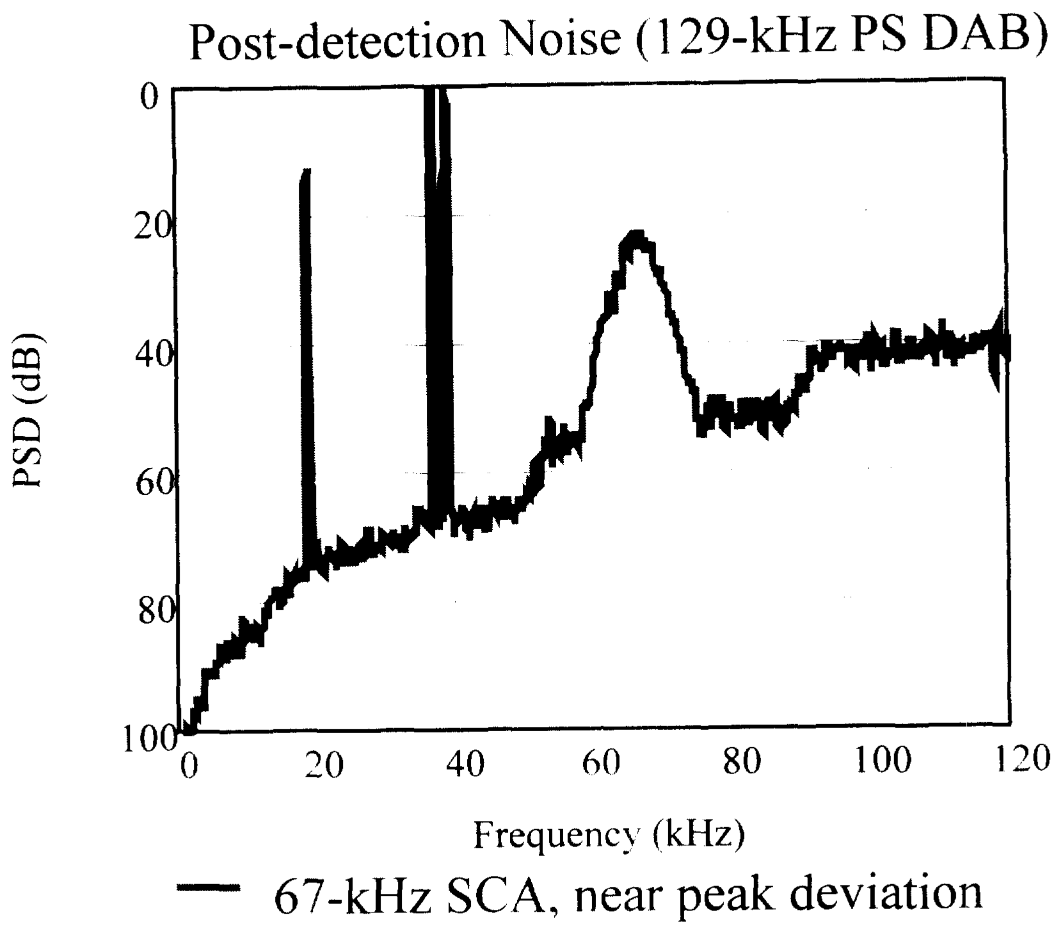

Figure E-17 - 67-kHz SCA Performance

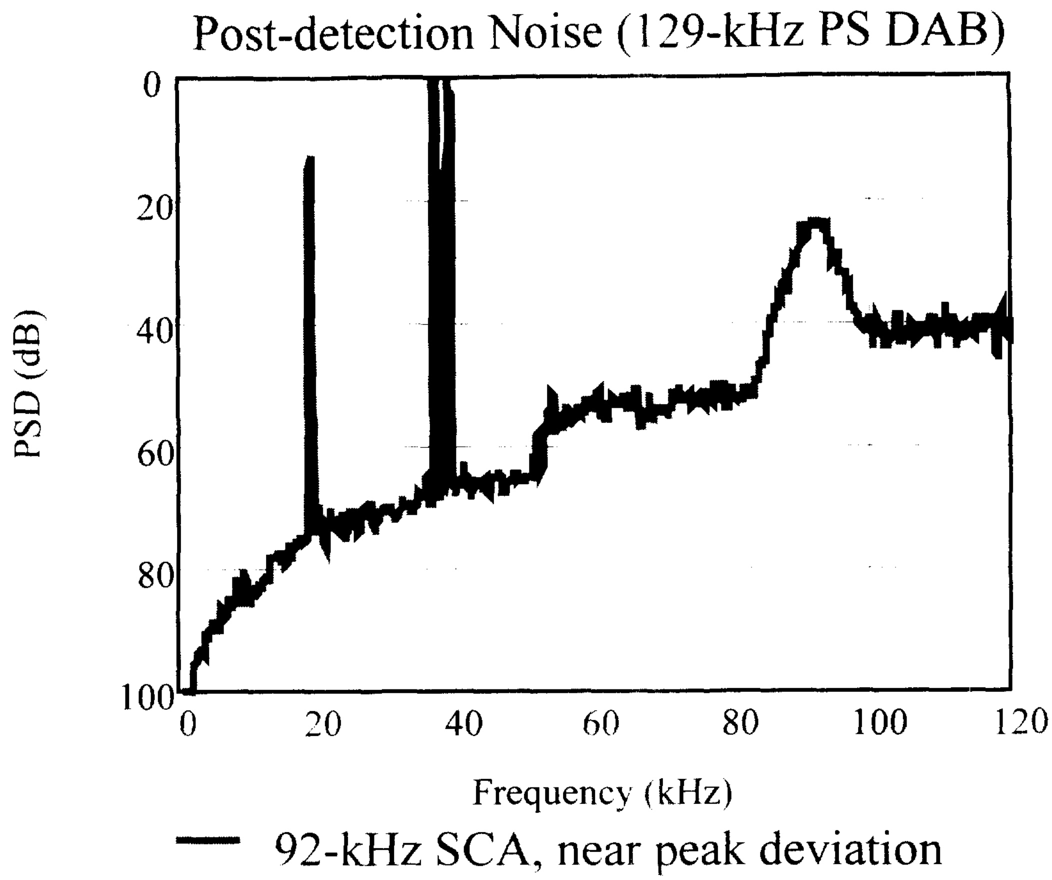

Figure E-18 - 92-kHz SCA Performance

4.1.3 Stereo subcarrier demodulation

Certain inexpensive FM stereo receivers may be susceptible to an increase in audio noise when receiving an IBOC DAB FM stereo signal. Investigations have revealed that this increase, should it occur, is the result of inadequate filtering of the post-detection baseband stereo multiplex signal. The current DAB waveform has been designed to mitigate this effect.

To recover the stereo information, the 30-kHz-wide, double-sideband amplitude-modulated ("DSB") left-minus-right ("L-R") signal centered at 38 kHz is demodulated using a 38-kHz local oscillator ("LO"), and subsequently filtered with a 15-kHz lowpass filter. In most receivers, the 38-kHz LO is simply a square wave, with a 38-kHz fundamental and odd harmonics at 114 kHz, 190 kHz, etc. As a result, in the absence of adequate filtering, not only is the desired L-R signal recovered, but so is any energy in the multiplex signal that lies within ±15 kHz of 114 kHz and 190 kHz.

In the presence of Gaussian noise only (no DAB), this effect is not pronounced. A well-known property of large-signal FM detection in Gaussian noise indicates that the power spectral density of the post-detection noise is directly proportional to the square of the frequency. Hence, the noise power spectral density at 114 kHz is 9 times that at 38 kHz (9.5 dB), and the noise at 190 kHz has 25 times the power (14.0 dB). High noise levels are mitigated because the amplitude of square-wave harmonics decreases with their order: if the 38-kHz fundamental has unit amplitude, the 114-kHz third harmonic has amplitude 1/3 (-9.5 dB), and the 190-kHz fifth harmonic has amplitude 1/5 (-14.0 dB). Therefore, the noise contribution from each harmonic is equal to the noise under the desired signal: this causes a 4.8-dB degradation due to Gaussian noise alone (without DAB) in receivers which do not filter the noise around their LO harmonics.

This decrease in SNR is avoided in well-designed receivers. Some receivers use "Walsh" decoders; others simply filter the baseband multiplex signal prior to DSB demodulation, which effectively eliminates components outside the desired L-R band. Most receivers – even those without such post-detection protection – should ameliorate the effects of the 190-kHz fifth harmonic by pre-detection filtering, since a good design would significantly filter the first adjacent FM signal centered 200-kHz from the desired channel.

Thus, today in the presence of Gaussian noise alone (analog only), certain inexpensive receivers which employ little or no post-detection protection experience up to a 3-dB stereo SNR degradation (from their DSB LO third harmonic) when compared to their more carefully